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A Re-examination of the ^{187}Re Bound on the Variation of Fundamental Couplings

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Abstract

We reconsider the ^{187}Re bound on the variation of the fine-structure constant. We combine the meteoritic measurement with several present-day lab measurements to firmly establish the quantitative upper limit to the time variation over the age of the solar system. We find that the relative change of the fine-structure constant between its present value and α of ~ 4.6 Gyr ago is consistent with zero, $\Delta\alpha/\alpha = [-8 \pm 8\ (1\sigma)] \times 10^{-7}$. We also rederive this bound in models where all gauge and Yukawa couplings vary in an interdependent manner, as would be expected in unified theories.

The prospect that the fundamental constants of nature vary in time is exciting and represents a radical departure from standard model physics. Recent attention to this problem has focused on the indication that the fine structure constant was smaller at cosmological redshifts $z = 0.5$–3.5 as suggested by observations of quasar absorption systems [1]–[4]. The positive result of $\Delta\alpha/\alpha = (0.54 \pm 0.12) \times 10^{-5}$, where $\Delta\alpha$ is defined as the present value minus the past one, is based on the many-multiplet method which makes use of the α dependence of the relativistic corrections to atomic energy levels.

However, there exist various sensitive experimental checks that constrain the variation of coupling constants (see e.g., [5, 6]). Among the most stringent of these is the bound on $|\Delta\alpha/\alpha|$ extracted from the analysis of isotopic abundances associated with the Oklo phenomenon [7]–[10], a natural nuclear fission reactor that occurred about 1.8 billion years ago. While the Oklo bound $|\Delta\alpha/\alpha| < 10^{-7}$ is considerably tighter than the "observed" variation, the Oklo phenomenon occurred at a time period corresponding to $z \approx 0.14$. It is quite possible that while α varied at higher redshifts, it has not varied recently. That is, there is no reason for the variation to be constant in time. Big bang nucleosynthesis also provides limits on $\Delta\alpha/\alpha$ [11, 12, 13]. Although these limits are weaker, they are valid over significantly longer timescales.

Bounds on the variation of the fundamental couplings can also be obtained from our knowledge of the lifetimes of certain long-lived nuclei. In particular, it is possible to use relatively precise meteoritic data to constrain nuclear decay rates back to the time of solar system formation (about 4.6 Gyr ago). Thus, we can derive a constraint on possible variations at a redshift $z \simeq 0.45$ bordering the range ($z = 0.5$–3.5) over which such variations are claimed to be observed. The pioneering study on the effect of variations of fundamental constants on radioactive decay lifetimes was performed by Peebles and Dicke [14] and by Dyson [15]. The isotopes which are most sensitive to changes in the Q value are typically those with the lowest β-decay Q-value, Q_β. The isotope with the smallest Q_β value (2.66 ± 0.02 keV) is ^{187}Re.

In Dyson's analysis [15], determination of ^{187}Re lifetime was based on (1) isotopic measurements of molybdenite ores [16], (2) isotopic measurements of iron meteorites [17], and (3) a direct measurement of the decay rate [18]. The decay constant was found to be $\lambda = (1.6 \pm 0.2) \times 10^{-11}$, $(1.4 \pm 0.3) \times 10^{-11}$, and $(1.1 \pm 0.1) \times 10^{-11}$ yr^{-1}, respectively. The discrepancy between the direct measurement and the geophysical ones led to speculations that this could be due to a time variation in the fine structure constant. Note that this would indicate a decreasing value of α from the past to the present, i.e., $\delta\alpha < 0$. However, the direct measurement [18] was complicated by many technical issues, and a later laboratory measurement [19] gave $\lambda = (1.5 \pm 0.2) \times 10^{-11}$ yr^{-1}, which was consistent with the geophysical measurements. As a conservative upper limit, Dyson [15] concluded from the above measurements that $|\Delta\alpha/\alpha| \le 5 \times 10^{-6}$ or $|\dot{\alpha}/\alpha| \le 5 \times 10^{-15}$ yr^{-1} over the last Gyr.

This was less stringent than the Oklo bound [8].

Recently, we have reconsidered the constraint on time variations of the fundamental couplings based on meteoritic measurements of the lifetimes of radioactive isotopes [20]. In particular, we made use of the dramatic improvement in meteoritic analyses of the ^{187}Re-^{187}Os system in iron meteorites. The present abundances of ^{187}Re and ^{187}Os in a meteorite are

$$
\begin{aligned}
(^{187}\mathrm{Re}) &= (^{187}\mathrm{Re})_i \exp(-\lambda t), && (1) \\
(^{187}\mathrm{Os}) &= (^{187}\mathrm{Os})_i + (^{187}\mathrm{Re})_i[1 - \exp(-\lambda t)], && (2)
\end{aligned}
$$

where the subscript "i" denotes the initial abundance and t is the age of the meteorite. Equations (1) and (2) give

$$
(^{187}\mathrm{Os}) = (^{187}\mathrm{Os})_i + (^{187}\mathrm{Re})[\exp(\lambda t) - 1]. \tag{3}
$$

Thus, there is a linear correlation (called an isochron) between the present abundances of ^{187}Os and ^{187}Re (measured relative to the reference stable isotope ^{188}Os, which does not receive any decay contributions).

The slope of this correlation, $\exp(\lambda t) - 1$, can yield the ^{187}Re decay constant λ if the age t is independently known. Radiometric data support the idea that the Group IIIA iron meteorites were formed at about the same time (± 5 Myr) as the angrite meteorites [21], which have a precisely determined ^{207}Pb - ^{206}Pb age of 4.558 Gyr [22]. The combination of this age with the slope of the well defined ^{187}Re - ^{187}Os isochron for IIIA iron meteorites gave $\lambda = (1.666 \pm 0.009) \times 10^{-11}$ yr^{-1} [21] (see also [23, 24]). The dominant contribution to the 1σ uncertainty is associated with the non-stochiometry of the Os salt used for calibration ($\approx 0.5\%$). Minor uncertainties include the Re - Os isochron slope, the ^{235}U and ^{238}U decay constants [25], the time difference between closure ages for U - Pb pair in angrites and the Re - Os pair in IIIAB iron meteorites.

The β-decay of ^{187}Re is a unique first fordidden transition, for which the energy dependence of the decay rate can be approximated as [26]

$$
\lambda \propto G_F^2 Q_\beta^3 m_e^2. \tag{4}
$$

As we showed previously [20], considering only the variation of the Coulomb term in Q_β, we have

$$
\frac{\Delta\lambda}{\lambda} = 3\frac{\Delta Q_\beta}{Q_\beta} \simeq 3\left(\frac{20\ \mathrm{MeV}}{Q_\beta}\right)\left(\frac{\Delta\alpha}{\alpha}\right) \simeq 2 \times 10^4 \left(\frac{\Delta\alpha}{\alpha}\right). \tag{5}
$$

Thus, given a determination of the possible variation in λ, we can obtain a limit on the variation of α. In our previous work [20], we assumed that the variation of λ cannot exceed the accuracy of the meteoritic measurements, $\Delta\lambda/\lambda < 0.5\%$. This gave $\Delta\alpha/\alpha < 3 \times 10^{-7}$ or $\dot{\alpha}/\alpha < 6 \times 10^{-17}$ yr^{-1} over a period of 4.6 Gyr, assuming a linear evolution with time.

Two issues concerning the above limit requires attention. The meteoritic ages used to derive the decay constant of ^{187}Re are determined in part by the decay constant of another radioactive isotope ^{238}U, which also depends on α. However, as noted earlier [20], this does not change our limit on $\Delta\lambda/\lambda$ because the decay constant of ^{187}Re is far more (by a factor of 40) sensitive to changes in α than that of ^{238}U. On the other hand, the assumption that the variation of λ cannot exceed the accuracy of the meteoritic measurements is not justified. Strictly speaking, this assumption is valid if measurements of comparable precision are made for meteorites with a large spread (e.g., several Gyr) in age and yield consistent decay constant for ^{187}Re. In practice, accurate measurements are available only for iron meteorites with essentially the same age. Thus, our earlier limit based on $\Delta\lambda/\lambda < 0.5\%$ over a period of 4.6 Gyr was over-restrictive.

To obtain a solid limit on $\Delta\lambda/\lambda$, we can compare the meteoritic measurements of λ, which cover 4.6 Gyr, with direct laboratory measurements, which give the present value $\lambda(t_0) = \lambda_0$. Indeed, there is a reasonably accurate direct measurement which yields $\lambda_0 = (1.639 \pm 0.025) \times 10^{-11}$ yr^{-1} [27] (see also [28]). The variation in λ is then $\Delta\lambda \ = \lambda_0 - \lambda = (-0.027 \pm 0.026) \times 10^{-11}$ yr^{-1}, or

$$\frac{\Delta\lambda}{\lambda} = -0.016 \pm 0.016. \tag{6}$$

As one can see, there is an insignificant trend in the negative direction. However, it is worth mentioning that the implication of the quasar absorption system measurements would be a *positive* $\Delta\lambda$, under the natural assumption that $\alpha(t)$ is a smooth monotonic function. This result and Eq. (5) give $\Delta\alpha/\alpha = [-8 \pm 8\ (1\sigma)] \times 10^{-7}$, which yields a 2σ limit

$$-24 \times 10^{-7} < \frac{\Delta\alpha}{\alpha} < 8 \times 10^{-7}. \tag{7}$$

This is weaker than the limit reported in [20] by a factor of ~ 3 for a positive $\Delta\lambda$ and by a factor of ~ 8 for negative $\Delta\lambda$. Even so, the $O(10^{-6})$ limits imposed by the meteoritic data still provide strong constraints on models of $\alpha(t)$ and severely restrict possibilities to accomodate the claimed variation of α based on observations of quasar absorption systems (see, e.g. Ref. [29]). This result is also about 6 times stronger than that given in [28] based on the meteoritic data of [24]. (We note that a more recent measurement [26] gave $\lambda_0 = 1.68 \times 10^{-11}$ yr^{-1} with a larger systematic uncertainty of $\approx 3\%$. Using a weighted average of the two direct measurements of λ_0 does not affect the above result significantly.)

It is important to note that this approach, i.e. the comparison of the meteoritic measurement of λ with λ_0, will benefit from any improvement in the determination of λ_0 which is required for the application of the Re - Os geochronology [30]. On the other hand, it is also important to recognize the limitations of this limit. Strictly speaking, if λ varies in time, then the meteoritic measurement really represents the time average of $\lambda(t)$ over the

age of the meteorite. As such, the redshift at which the limit can be applied will in principle depend on the specific functional dependence of $\lambda(t)$. For example, if we consider a simple mononomial form, $\lambda(t) - \lambda_0 \sim (t_0 - t)^n$, then the limits (6) and (7) should be applied at a reduced look-back time of $(t_0 - t) = 4.6\text{Gyr}/(n+1)^{1/n}$. As noted above, a look-back time of 4.6 Gyr corresponds to a redshift of $z \sim 0.45$ for the assumed cosmological model, hence the limit would be applied (in a model dependent way) at a somewhat smaller redshift. For example, in the linear case, $n = 1$, one can either apply our limits above at a time $t_0 - t = 2.3$ Gyr, or one can apply a relaxed limit (by a factor of 2) at a look-back time of 4.6 Gyr. Because of the model dependence, it may be possible with a careful choice of a time dependence for λ to obviate this limit [31] due to the limit being tied to a time average of the decay rate.

As we discussed previously, in the context of unified or string-inspired theories, all Yukawa couplings and gauge couplings depend on the same moduli fields and the change in the fine structure constant typically implies a change in other couplings and mass scales [12, 32]. The dominant effects are found in induced variations of the QCD scale Λ and the Higgs expectation value v. The variations $\frac{\Delta\Lambda}{\Lambda} \simeq 30\frac{\Delta\alpha}{\alpha}$ and $\frac{\Delta v}{v} \sim 80\frac{\Delta\alpha}{\alpha}$ [12, 33, 34] are translated into variations in all low energy particle masses. In short, once we allow α to vary, virtually all masses and couplings are expected to vary as well, typically much more strongly than the variation induced by the Coulomb interaction alone. In Ref. [20], we adopted $|\Delta\Lambda/\Lambda - \Delta v/v| \sim 50\Delta\alpha/\alpha$. The contributions to Q_β from (the kinetic energy) T and (the nuclear potential energy) V, which scale with Λ, are comparable to that from the dominant Coulomb term (C), which scales as $\alpha\Lambda$. As changes in Λ are $O(30)$ times larger than that in α, we can estimate

$$\frac{\Delta\lambda}{\lambda} = 3\frac{\Delta Q_\beta}{Q_\beta} - 2\frac{\Delta v}{v} \simeq 3\frac{T(V,C)}{Q_\beta}\frac{\Delta\Lambda}{\Lambda} \simeq 2\times 10^4\frac{\Delta\Lambda}{\Lambda}, \tag{8}$$

which gives

$$-8\times 10^{-8} < \frac{\Delta\alpha}{\alpha} < 3\times 10^{-8}, \tag{9}$$

over a period of 4.6 Gyr.

In summary, we have revisited the bounds on the change of the fine-structure constant from the ^{187}Re meteoritic measurements. We have shown that these limits are determined by the accuracy of the laboratory determination of the decay rate. This results in a bound, $\Delta\alpha/\alpha = (-8\pm 8)\times 10^{-7}$ going back to ~ 4.6 Gyr ago, that is of significant importance for all models of $\alpha(t)$.

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